Possibilistic NDT data fusion for evaluating concrete structures

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Abstract

A new application of data fusion is presented within the context of national research project named SENSO. The aim is to improve evaluation of indicators or pathologies of in situ concrete structures by combining measurements from different NDE techniques (radar, electrical resistivity and capacity, infrared thermography, impact echo and ultrasounds). Every non-destructive measurement is likely to provide an estimation of the unknown indicators with a certain confidence that is function of its reliability and its sensitivity to each indicator. When the estimations converge data fusion improves final confidence. In case of disagreement conflict can be managed by specific operators. We develop an adapted solution based on possibility theory that is particularly used in case of imprecise and uncertain data. This theory is very flexible in term of data representations and fusion operators and then requires adapted choices at every step of fusion process. Results are presented for simultaneous evaluation of water saturation and porosity ratio. They show that the chosen adaptative operator function of reliability is appropriate to the problem.

Résumé

Une nouvelle application du procédé de fusion de données est présentée, dans le contexte du projet ANR SENSO. L'objectif est d'améliorer l'évaluation d'indicateurs ou de pathologies sur des structures en béton, en combinant des mesures provenant des différentes techniques de CND (radar, résistivité et capacité électrique, thermographie infrarouge, impact écho et ultrasons). Chaque mesure non destructive est susceptible de fournir une estimation des indicateurs recherchés, avec une certaine confiance fonction de sa fiabilité et de sa sensibilité à chaque indicateur. Lorsque les estimations convergent, la fusion des données augmente la confiance finale. En cas de désaccord entre les informations, le conflit peut être géré par des opérateurs spécifiques. Nous développons une solution adaptée basée sur la théorie des possibilités, particulièrement utilisée dans le cas de données imprécises et incertaines. Cette théorie est très souple en terme de représentation des informations et d'opérateurs de fusion, et elle nécessite donc de faire les bons choix à chaque étape du processus de fusion. Les résultats obtenus à partir de quelques observables sont présentés dans le cas de l'évaluation simultanée du taux de porosité et de la saturation en eau. Ils montrent que le choix d'un opérateur adaptatif fonction de la fiabilité est bien approprié au problème.

Keywords

Quantitative estimation, water saturation, porosity rate, concrete

1 SENSO project and data fusion

Reliability of diagnosis and degradation anticipation represent a major economic stake in term of patrimony administration. The adopted methodology of NDE must provide relevant data and allow extracting reliable and useful information. The problem particularly encountered for concrete structures is the sensitivity of NDE techniques to many characteristics of the material itself (heterogeneity…) and of its environment. Thus reliable information is often difficult to extract. Data fusion makes use of the complementarity of data to improve diagnosis reliability.

French project named SENSO aims at improving the assessment of in situ concrete structures by providing quantitative evaluation of the following indicators: porosity rate, water saturation, modulus of elasticity, mechanical strength, chloride content and carbonatization degree, by using and combining different NDE methods. We present here the study regarding simultaneous estimation of two of these indicators: porosity rate and water saturation, for sane concretes.

A large measurement campaign in laboratory was achieved on a representative range of concretes. Thus 90 specimens were made with controlled compositions and w/c ratios and they were conditioned at different levels of water saturation. Then a large range of NDE techniques (radar, electrical resistivity and capacity, infrared thermography, impact echo and ultrasounds) have been operated to characterize and quantify their dependence to indicators' variations. Around 80 measurable quantities, named "parameters" in the following, were identified.

This large database allowed assessing empirical relations (bilinear regressions) between each parameter and the two varying indicators. Knowing these correlations and associated variabilities is indispensable as an input for the chosen data fusion process based on possibility theory.We describe the three steps of data fusion process: 1) description of measured data with trapezoidal possibility distributions that are function of the variability of each technique, 2) combination of the obtained possibility distributions, and 3) decision criterion.

2 Data fusion and possibility theory applied to concrete NDE

Data fusion using possibility theory enables combining heterogeneous information more or less precise and reliable to provide global information with increased quality. This theory is more appropriate for estimation problem than methods based on classification (as Dempster-Shafer theory) commonly used in NDT domain for image fusion for example [1,2,3].

Note that two measurements would theoretically be sufficient to determine two unknown indicators by solving a set of two equations (inversion process). But imperfections of measurement and partial reproducibility lead to the need of improving diagnosis quality. In fact correlations are approximations of the reality including experimental and modelling errors. Relative disagreement or even conflict between the sources of information can then result and data fusion process enables to manage such situations.

Possibility distributions

Possibility distribution representation allows modelling imprecise information [4,5]. A possibility distribution of a parameter x is classically written as π_x. Then $\pi_x(u)$ takes values between 0 and 1 and designates the degree of possibility for having $x=u$:

- $\pi_x(u) = 0$ means that $x=u$ is impossible,
- $\pi_x(u) = 1$ means that nothing impedes x to equals u,
- there is at least one value u^* such as $\pi_x(u^*) = 1$ (normalization condition).

Values of u for which $0 < \pi_x(u) \leq 1$ constitute the fuzzy set of possible values of x.

Combination of distributions

Combination is equivalent to find agreement and disagreement areas between the sources to extract one ore more information reliable enough. There is no universal combination operator for the whole problems. The main difficulty in the choice of operator is to find a good compromise between precise but certainly wrong result, and certain but too imprecise one.

Fundamental operators of possibility theory are [4,6,7] :

- Conjunctive mode (logical operator "and"), with severe behaviour (t-norms).
- Disjunctive mode (logical operator "or"), with indulgent behaviour (t-conorms).

Table 1 shows examples of the most commonly used t-norms and t-conorms. Fig. 1 represents two examples of combination of three initial distributions.

Table 1. *Examples of T-norms et t-conorms the more common [7]*

name	t-norm	dual t-conorm
Zadeh	$\min(\pi_1,\pi_2)$	$\max(\pi_1,\pi_2)$
Probabilistic	$\pi_1.\pi_2$	$\pi_1 + \pi_2 - \pi_1.\pi_2$
Lukasiewicz	$\max(0,\pi_1 + \pi_2 - 1)$	$\min(1,\pi_1 + \pi_2)$

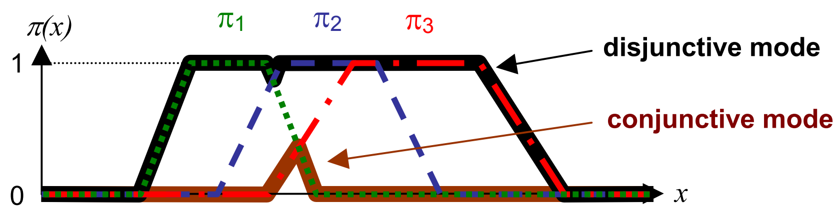

Figure 1. *Zadeh t-norm and t-conorm for combination of 3 distributions*

The whole operators are based on these two fundamental modes. Method to be adopted depends on required properties, conflict level and sources reliability. Some operators, more elaborated, adapt themselves their behaviour (from conjunctive to disjunctive via compromise) as a function of the situation. These are named "adaptative" operators.

Decision criteria

The two most commonly used criteria are:

- Criterion of maximum: solution corresponds to the maximum degree of possibility reached by the fused distribution.
- Criterion of threshold: a threshold of possibility degree is defined and solutions are those which degree of possibility is greater than this value.

Note that the area of threshold criterion solutions can moreover inform about precision and/or reliability of the result.

3 Knowledge modelling in SENSO

Required data for distribution construction are: standard deviation of each parameter measurement (from statistical processing of measurement campaign), correlation linking each parameter to the indicators, and value of each measured parameter.

Possibility distributions construction in terms of "parameter"

When information come from sensors, possibility distribution enables to generalise error band notion. Several representations were tested (Gaussian, triangular and trapezoidal). Trapezoidal shape was selected (see fig. 2) because it reduces to zero at the ends that excludes values too far, and the flat area with degree of possibility equal to 1 means that some values are as possible as each other. Building of the trapeze is based on measured value and standard deviation of the parameter.

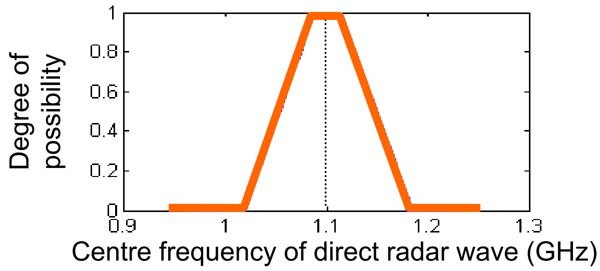

Figure 2. *Example of possibility distribution for a measured radar frequency of 1.1 GHz*

Construction of the possibility distributions in terms of indicators

Searched solutions being values of porosity rate and water saturation, distributions to be combined have to be expressed as functions of these indicators. So extension principle (see fig. 3) is applied [6] to the previously constructed distributions by using correlations linking parameter and indicators (these correlations are empirical and obtained from measurement campaign byapplying bilinear regression).

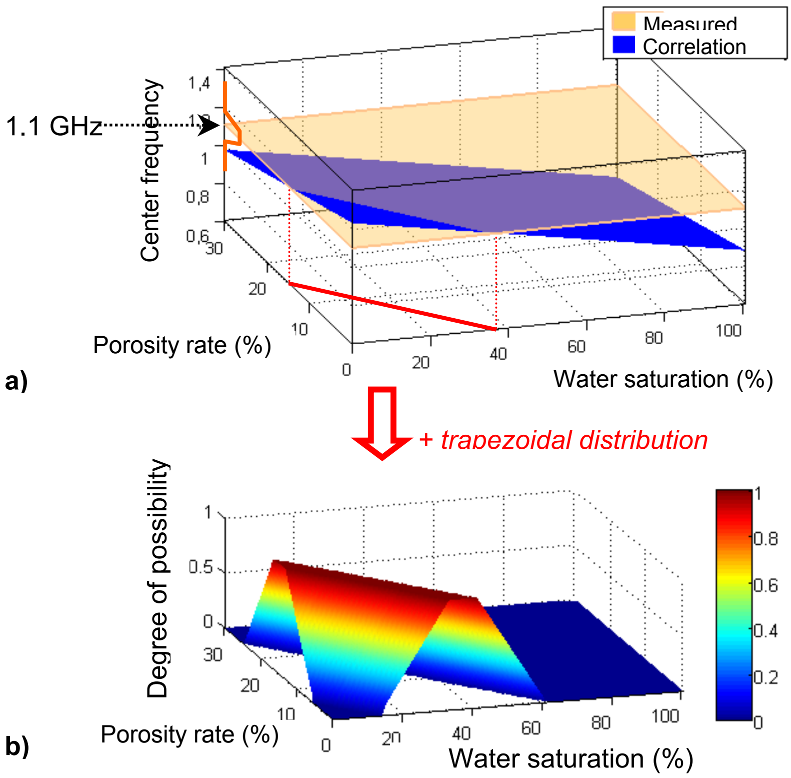

Figure 3. *Extension principle: a) bilinear correlation linking radar center frequency and {porosity rate ; water saturation}, b) possibility distribution to be combined*

Then every measured value provides one possibility distribution. Visualisation of the distributions gives an account of possible values of {porosity rate; water saturation} from each measurement. Fig. 4 shows three examples of projected distributions. One can note that ultrasonic surface wave velocity is weakly sensitive to water saturation as far as one measure provides the whole values of saturation as possible. On the contrary capacitive measure is weakly sensitive to porosity rate, and radar wave velocity is sensitive to both indicators.

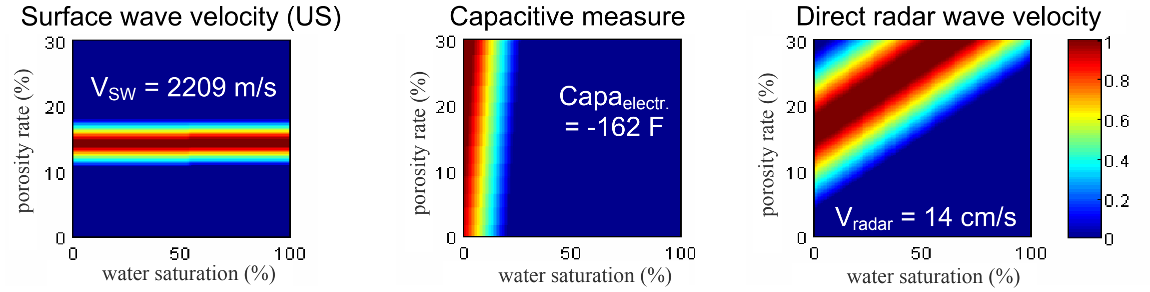

Figure 4. *Examples of distributions obtained from measures of different parameters*

4 Chosen operator of combination

Different operators were tested [7,8,9]. We finally chose an adaptative operator developed by Delmotte [8] and which adapts its behaviour as a function of conflict level and mean reliability of the different sources of information:

$$\pi(p,s) = \left(1-\alpha^2\right)\max_i\left(t_i\pi_i(p,s)\right) + \alpha^2 \min\left[\min_i\left(1-t_i+t_i\pi_i(p,s)\right), \max_i\left(\pi_i(p,s)\right)\right] \quad (1)$$

where p and s designate porosity rate and water saturation, $\pi_i\ (p,s)$ is the distribution provided by source i, t_i is the global reliability of source i and $\alpha = 1/n \sum_{i=1..n} t_i$ is arithmetic mean of reliabilities of the n sources of information.

This operator implies that: 1) when only few sources are reliable, α tends towards 0 and adopted behaviour tends towards disjunctive mode ("max" of the 1st term), 2) conversely if most of sources are reliable, behaviour is rather conjunctive ("min" of the 2nd term).

Global reliability is calculated from "intrinsic reliability" of the source (here: quality index coming from statistical processing of measurement campaign), and "concordance reliability" computed for each distribution relatively to all the other sources information.

5 Data fusion results

Fig. 5 shows an example of initial distributions to be fused and the resulting fused distribution. Distributions provided by the parameter measurement are in good agreement, and final distribution clearly points a peak of solution.

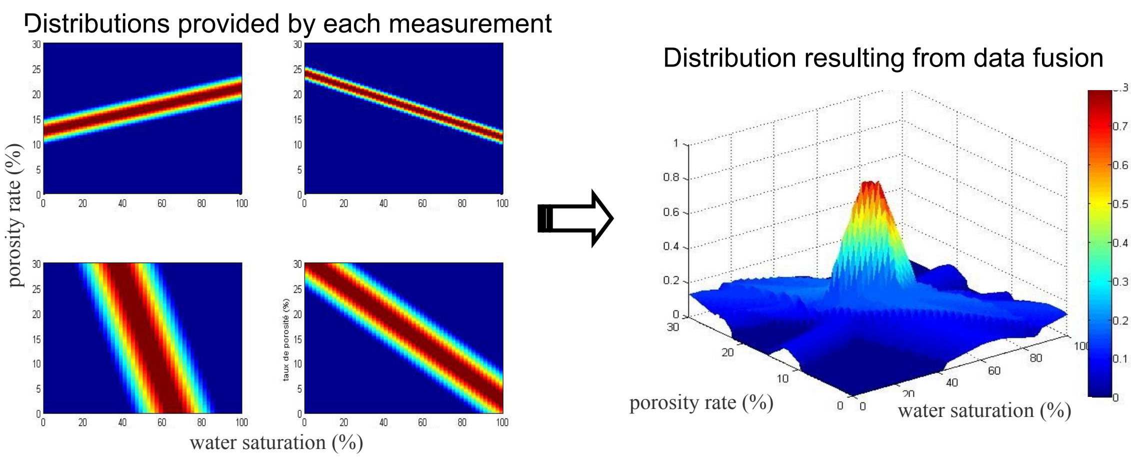

Figure 5. *Example of data fusion process visualisation*

For better readability reasons, maximum criterion is chosen to present in table 2 some results for 5 specimens. We observe a good agreement between experimental values of the indicators obtained destructively and values obtained from data fusion process with 4 chosen parameters. Maximum gap equals to 2.5 % for porosity rate and 5.5 % for water saturation.

Table 2. *Comparison of destructively measured indicators with result of fusion*

	Specimen :	G2E3	G2E7	G3E3	G3E4	G3E9
Porosity rate (%)	Experimental	14.3	**14.3**	15.5	15.5	15.5
	From fusion	*14.4*	***16.8***	*17.4*	*17*	*15.8*
Water saturation (%)	Experimental	38.7	70.6	29.2	51.5	**73.5**
	From fusion	*34*	*68*	*26*	*50*	***68***

6 Conclusions

Data fusion in SENSO aims at estimating indicators of concrete structures from several NDE techniques. Estimation provided by each individual technique is uncertain and imprecise mostly because of empirical correlations establish between parameters and indicators. Therefore data fusion based on possibility theory was chosen.

Different choices were done concerning distribution shape, fusion operator and decision criterion. Selected operator adapts his behaviour as a function of reliability of the sources and conflict level.

Selection of complementary techniques to be combined is essential for a better estimation of indicators and so to improve diagnosis. Finally applications provide a good agreement between predicted and expected values of porosity and saturation.

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